Measurement of Linear Polarization of Positron Annihilation Photons.

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Summary. — The linear-polarization correlation of γ-rays from positron annihilation in copper and plexiglass was measured under various experimental conditions. Both the absolute degree of linear polarization and its dependence on the source-polarimeter distance were found in agreement with quantum-mechanical predictions.

1. – Introduction.

1'1. *General remarks.* – The discussion about the foundations of quantum mechanics (QM), which was in the past mainly philosophical in character, assumed a physical significance few years ago, when it was found that the choice among different descriptions of certain microscopic systems can be influenced by the results of some experiments.

According to their characters, such experiments can be schematically divided into different classes, *viz.*

i) Experiments conceived on the basis of the so-called Einstein, Podolsky and Rosen (EPR) paradox (1). They consist, in principle, in the measurement of the correlation between the spins of the two particles coming out from the spontaneous disintegration of a spinless original system.

As pointed out by BOHM and AHARONOV (2), the 511 keV γ-rays emitted

(1) A. EINSTEIN, B. PODOLSKY and N. ROSEN: *Phys. Rev.*, **47**, 777 (1935).
(2) D. BOHM and Y. AHARONOV: *Phys. Rev.*, **108**, 1070 (1957); *Nuovo Cimento*, **17**, 964 (1960).

from the annihilation of the electron-positron system in the $^{-}S_0$-state fulfil the previous theoretical requirement and are much more easy to handle than massive particles in carrying on polarization correlation experiments.

ii) Experiments consisting in the measurement of the polarization correlation between optical photons emitted in appropriated atomic cascades. Even if this kind of experiments, strictly speaking, does not fulfill the EPR requirements, nevertheless, as suggested by CLAUSER *et al.* ([3]), the states of polarization of the widely separated photons must be strongly quantum-mechanically correlated.

iii) Experiments involving massive particles ([4]).

They are based on the measurement of the degree of polarization correlation between the outgoing protons produced in the pp scattering at low energies.

All these experiments give important information when their results are compared with the different quantitative consequences of such assumptions as the following:

a) QM holds. The observed system is described by a state vector which is the superposition of the products of the eigenvectors corresponding to the two opposite polarization states (mixtures of the 2nd kind).

b) The observed system is described by a mixture which is simply the product of the state vectors of the two individual subsystems (mixtures of the 1st kind).

c) The result of a measurement on a microscopic system follows the predictions of the local hidden-variable (LHV) theories and not those of the ordinary QM. Bell's inequality holds as well as its consequences.

The results of the experiments performed to test these assumptions are not in perfect agreement with each other. All the experiments of the first two classes seem to rule out the hypothesis of the existence of mixtures of the 1st kind for distances between the photons comparable with the coherence length.

As far as the choice between the QM and the LHV theory is concerned, there is a disagreement between experiments belonging both to the same class and to different classes, and further experimental efforts are therefore needed in order to gain an unambiguous conclusion.

([3]) J. F. CLAUSER, M. A. HORNE, A. SHIMONY and R. A. HOLT: *Phys. Rev. Lett.*, **23**, 880 (1969).

([4]) M. LAMEHI-RACHTI and W. MITTIG: *Colloque: Un demi siècle de mécanique quantique* (Strasbourg, 1974).

1·2. *Survey of the experimental results.* – Let us start from the third class. We have here only one experiment [4]; its results are in agreement with hypothesis *a*).

In the second class we have four published results. The first, by FREEDMAN and CLAUSER [5], is in agreement with hypothesis *a*) for a 0-1-0 cascade in calcium. The second, by HOLT and PIPKIN [6], gives exactly the opposite result from a measurement of a 1-1-0 cascade in ^{198}Hg, being in agreement with hypothesis *c*).

The other two experiments [7] give results in perfect agreement with hypothesis *a*).

The experiments of the first class can be divided into two groups, *i.e.* the experiments performed earlier than 1960 and those performed later than 1970. Among the formers, the results really significant from the point of view of our discussion are those by WU and SHAKNOV [8] and by LANGHOFF [9], which are in agreement with the prediction of QM.

The recent experiments have been performed by KASHDAY *et al.* [10] and by FARACI *et al.* [11].

The former exploits the γ-rays due to the annihilation of positrons coming from a ^{64}Cu radioactive β^+ emitter. This experiment measures very accurately the asymmetry in the counting rate as a function of the azimuthal angle, due to the linear-polarization correlation.

The results are in agreement with QM even if, due to the low efficiency of the Compton polarimeter, hypothesis *c*) cannot be ruled out without any extra assumption.

The latter experiment, in which a ^{22}Na positron source was used, leads, on the contrary, to the opposite result. The experimental data are in agreement with the upper limit of the Bell inequality and in quite complete disagreement with the predictions of QM.

The authors point out, moreover, that an attenuation of the asymmetry seems to take place when the distance of the source from the scatterers exceeds the coeherence length of the photons (*), a result which should be ex-

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(5) S. J. FREEDMAN and J. F. CLAUSER: *Phys. Rev. Lett.*, **28**, 938 (1972).
(6) R. A. HOLT and F. M. PIPKIN: preprint (unpublished).
(7) J. F. CLAUSER: *Phys. Rev. Lett.*, **36**, 1223 (1976); E. S. FRY and R. C. THOMPSON: *Phys. Rev. Lett.*, **37**, 465 (1976).
(8) C. S. WU and I. SHAKNOV: *Phys. Rev.*, **77**, 136 (1950).
(9) H. LANGHOFF: *Zeits. Phys.*, **160**, 186 (1960).
(10) L. R. KASHDAY, J. D. ULLMAN and C. S. WU: *Nuovo Cimento*, **25** B, 633 (1975).
(11) G. FARACI, D. GUTKOWSKI, S. NOTARRIGO and A. R. PENNISI: *Lett. Nuovo Cimento*, **9**, 607 (1974).
(*) After completion of our experiment we learned of a more recent experiment [12] in contradiction with this conclusion and in agreement with our findings.
(12) A. R. WILSON, J. LOWE and D. K. BUTT: *J. Phys. G*, **2**, 613 (1976).

pected in the case of the transition of the two-photon system to a mixture of the first kind, as suggested by BOHM and AHARONOV (2).

It turns out that all these results seem to support the QM rather than the LHV theory; nevertheless, the existing discrepancies do not allow any satisfactory conclusion.

Further experiments should be therefore performed in order to check, in particular, both the Bell inequality and the dependence of the asymmetry on the distance between the source and the scatterers.

Along this line, we have carried out a new measurement of the polarization correlation between annihilation quanta whose description and results are reported in the following sections.

2. – Experimental.

2'1. *The apparatus.* – In the present experiment the polarization correlation of annihilation quanta was measured by a conventional Compton polarimeter.

A ^{22}Na radioactive source with an activity of 0.1 mCu and a diameter less than 7 mm was used as positron emitter.

The source was shielded by two nickel foils, each 5 μm thick. The source was also covered by two discs each 5 mm thick, which were used as annihilators. Copper and plexiglass were in turn used as annihilating materials. See subsect. **2'2** for details.

The source was lodged at the centre of a cilindrical lead housing with a thickness of about 5 cm in all directions and with a cylindrical window along its axis, acting as a collimator of the γ-rays.

Two plastic scintillators, placed on both sides of the collimator, were used as scatterers for the γ-rays emitted from the source and as detectors for the scattered Compton electrons.

The scattered γ-rays were detected by NaI(Tl) scintillators which were protected by a cylindrical lead shield 1.2 cm thick, in order to prevent the γ-rays scattered by the mechanical supports to be detected.

The dimensions of the NaI(Tl) detectors and their distance from the scatterers were held constant during the experiment. In fig. 1 the dimensions and the relative locations of the detectors are sketched. The size and the positions of the scatterers were changed during the experiment.

The electronics consisted in fast-slow coincidence systems recording the 2-fold coincidence between the plastic counters, the 3-fold coincidences between plastic scintillators and each of the NaI(Tl) counters and the 4-fold coincidence between plastic scintillators and both NaI(Tl) counters.

As shown in fig. 2, where the block diagram of the electronics is sketched, the analogous pulses from each counter belonging to the same arm of the Compton polarimeter were added together and then analysed in amplitude in order to record the 511 keV annihilation γ-rays only.

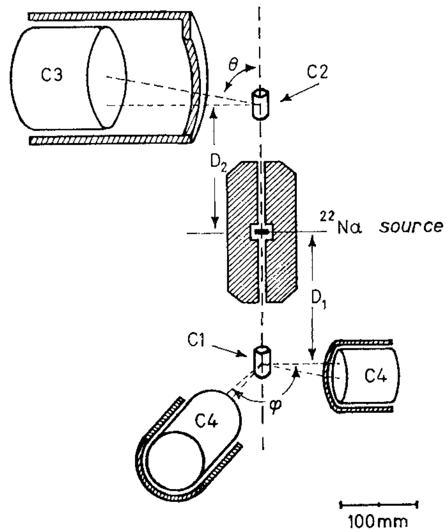

Fig. 1. – Schematic view of the experimental arrangement. C1 and C2 are the plastic scatterers; C3 and C4 are the NaI(Tl) detectors. ▨ lead shields.

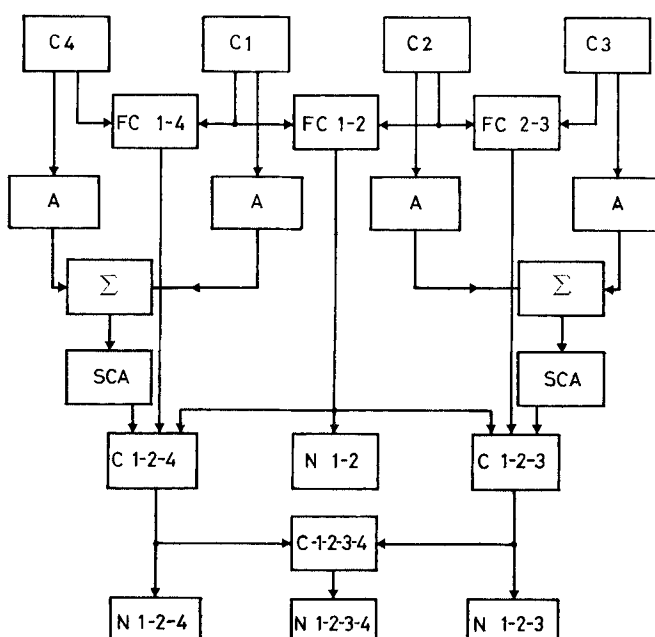

Fig. 2. – Block diagram of the electronics: FC = fast coincidence, A = amplifier, $\sum$ = sum amplifier, SCA = single-channel analyser, C = coincidence, N = scaler.

With such an energy selection, together with the chosen resolving time for the coincidence circuits, the number of random events of any type was absolutely negligible.

2'2. *The method.* – The absolute degree of linear polarization and its dependence from the distance of the scatterers from the source are the outcomes of the present experiment.

If φ is the angle between the planes of scattering of the two γ-rays and N is the rate of the various types of coincidences recorded at this angle, then the degree of linear polarization can be obtained by measuring the quantity

$$R(\varphi) = \frac{N_{12} \cdot N_{1234}}{N_{123} \cdot N_{124}}$$

at different values of φ or, more conveniently if the counting rate is low, by measuring the quantities

$$B = \tfrac{1}{2}\left[R(90^\circ) - R(0^\circ)\right]$$

and

$$A = \tfrac{1}{2}\left[R(90^\circ) + R(0^\circ)\right] .$$

Owing to the chosen definition of $R(\varphi)$, the quantity A must be equal to unity and B represents, therefore, the absolute degree of linear polarization.

The particular value of A, being determined in advance, allows a significant self-consistent check on the experimental results.

The value of $R(\varphi)$, moreover, is nearly independent of small instabilities in the gain of the electronic chains and of geometrical misalignements in the detector positioning.

With such a choice of $R(\varphi)$ the most important source of instrumental errors is eliminated.

There are nevertheless some possible sistematical errors not eliminated by the choice of the parameter R. The most obvious among them consists in neglecting the effects of the multiple Compton scattering in the scatterers.

In order to take it into account, B was measured at different angles θ of scattering with scatterers of different sizes.

The difference in the results can be used to obtain the correction for the attenuation of the correlation parameter B.

A second source of attenuation of B could arise from the actual process of positron interaction in matter. In fact, if the annihilation does not take place in the $^1S_0$-state only, but there is also a contribution of higher angular momenta, the degree of polarization correlation might be significantly reduced.

If this is the case, one could expect different values of B using annihilators with strongly different physical properties. We have, therefore, measured the value of B using both copper and plexiglass as annihilation materials.

Finally, the position of the scatterers with respect to the source was changed, so that both the sum and the difference of the distances between the scatterers and the source assumed values ranging from one to ten times the coherence length of the annihilation photons, which, in copper, is about 7 cm.

3. – The results.

In order to evaluate the effect of multiple scattering, the value of B was measured for $\theta = 60°$, $82°$, $98°$ under two experimental conditions.

In the first condition, the scatterers were equal in size, *viz.* 3 cm long and 2 cm in diameter each. In the second case, the diameter of the scatterers was reduced to 0.5 cm.

If we assume that the probability of multiple Compton scattering is roughly proportional to the volume of the scatterers, the multiple scattering should not practically take place in the arm of the polarimeter containing the thin scatterer, and its overall effect on B should be approximately halved.

The results are reported in table I, together with the results of a Monte Carlo calculation, under the three considered theoretical assumptions, of the value of B in the actual experimental geometry.

In the third column of table I is reported the correction for the multiple Compton scattering and in the fourth column is reported the corrected experimental value of B.

It turns out from table I that the effect of multiple scattering on B is decreasing with increasing θ and becomes nearly negligible for $\theta \simeq 98°$.

We have chosen, therefore, this angular situation for further measurements. In fig. 3 the experimental values of $R(\varphi)$ as functions of φ are reported, together with the theoretical behaviour of $R(\varphi)$ according to the QM, the LHV theory and Bohm and Aharonov (BA) hypothesis.

TABLE I. – *Experimental results and theoretical values of B for finite geometry.*

θ (*)		$d_1 = d_2 = 2$ cm	$d_1 = 2$ cm, $d_2 = 0.5$ cm	Correction on B	Corrected B	QM	Bell limit	BOHM-AHARONOV (2)
60°	A	0.989 ± 0.006	1.001 ± 0.016					
	B	0.243 ± 0.006	0.285 ± 0.016	0.091 ± 0.038	0.333 ± 0.038	0.301	0.213	0.151
82°	A	0.995 ± 0.005	1.008 ± 0.012					
	B	0.351 ± 0.005	0.372 ± 0.012	0.043 ± 0.026	0.394 ± 0.026	0.396	0.280	0.198
98°	A	0.995 ± 0.005	0.998 ± 0.009					
	B	0.290 ± 0.005	0.305 ± 0.009	0.035 ± 0.022	0.325 ± 0.022	0.318	0.225	0.159

(*) Average scattering angle.

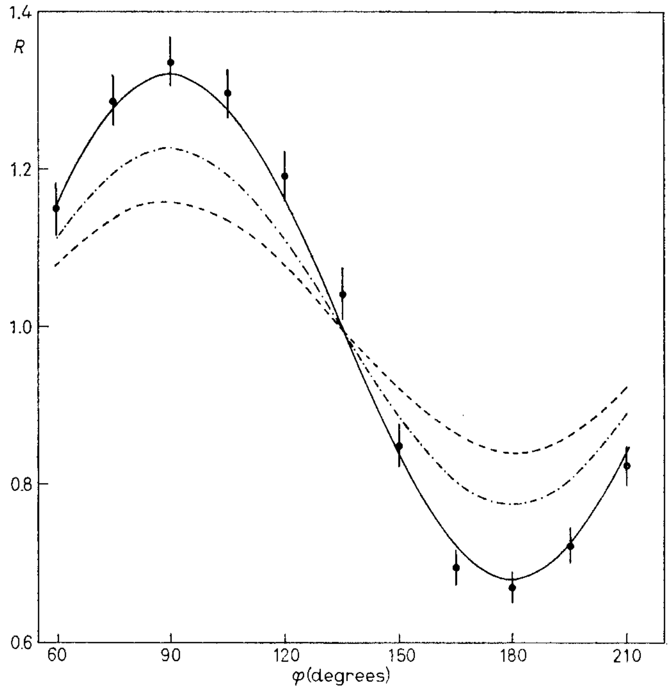

Fig. 3. – Plot of experimental values of R *vs.* the relative azimuthal angle. Full line: theoretical prevision, for finite geometry, for 2nd-kind mixture; dashed line: theoretical prevision, for finite geometry, for 1st-kind mixture; dot-dashed curve: theoretical prevision, for finite geometry, for Bell's limit.

The distance between the scatterers and the source is in this case about 10 cm, *viz.* of the same order of magnitude of the coherence length of γ-rays for positron annihilation in copper ($\approx$ 7 cm).

In table II, the results of B at different distances between the source and the scatterers are reported.

TABLE II. – *Experimental A and B for $\theta = 98°$ at different values of the flight paths of the two photons.*

D_1 (cm)	D_2 (cm)	A	B (*)	Annihilator
11.5	12.5	0.095 ± 0.005	0.325 ± 0.022	copper
30	60	1.006 ± 0.018	0.346 ± 0.028	copper
11.5	82.5	0.988 ± 0.024	0.363 ± 0.033	copper
9	41	0.993 ± 0.009	0.319 ± 0.022	copper
11.5	12.5	0.995 ± 0.008	0.326 ± 0.023	plexiglass

(*) Corrected for multiple scattering.

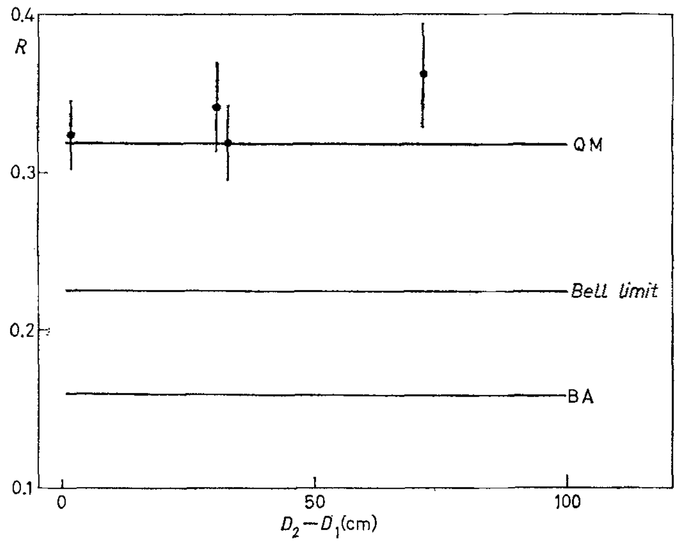

Fig. 4. – Plot of experimental values of $R(98°)$ *vs.* the difference in the flight paths of the two photons.

In the same table, one result from the plexiglass annihilator is also plotted.

The same results as functions of $D_2 - D_1$ and of $D_2 + D_1$ are plotted, respectively, in fig. 4 and 5.

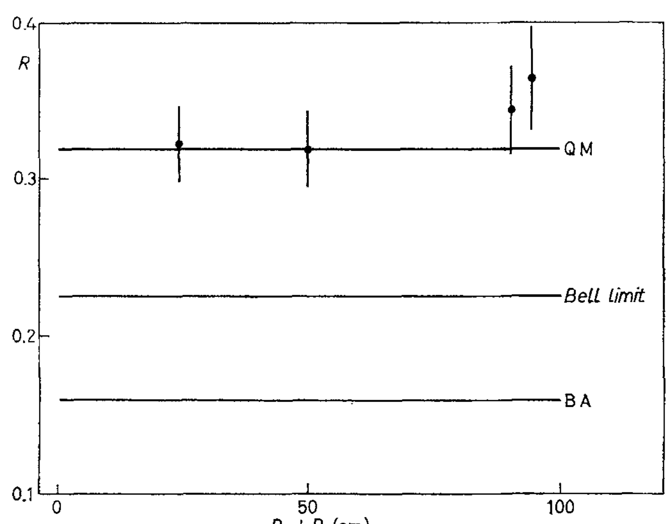

Fig. 5. – Plot of experimental values of $R(98°)$ *vs.* the sum of the flight paths of the two photons.

4. – Conclusion.

The results of the present experiment are in satisfactory agreement with the prediction of QM for the polarization correlation under the particular experimental conditions considered here.

Of course, as already suggested in the introduction, these results are not in principle sufficient to rule out Bell's inequality without assuming that the degree of polarization with ideal polarizers is obtained by dividing the experimental value of B by the efficiency of the polarimeter. An assumption which seems, nevertheless, quite reasonable.

From the results plotted in fig. 4 and 5, moreover, there is no evidence for the loss of linear-polarization correlation in a range of distances between the scatterers as wide as 10 coherence lengths.

It clearly rules out the hypothesis of a transition from a mixture of the second kind to a mixture of the first kind and gives further support to quantum-mechanical predictions.

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● RIASSUNTO

Si è misurata la polarizzazione lineare dei fotoni emessi nell'annichilazione di positroni in rame e plexiglass. Sia il grado di polarizzazione che la sua dipendenza dalla distanza fra sorgente e polarimetro sono risultati in accordo con le previsioni della meccanica quantistica.

Измерение линейной поляризации фотонов, образованных при аннигиляции позитронов.

Резюме (*). — При различных экспериментальных условиях была измерена корреляция линейной поляризации гамма-лучей, образованных при аннигиляции позитронов в меди и в плексигласе. Были определены абсолютная степень линейной поляризации и ее зависимость от расстояния между источником и поляриметром. Полученные результаты согласуются с предсказаниями квантовой механики.

(*) *Переведено редакцией.*